

Negative-Pressure Wound Therapy in the Military: Lessons Learned

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Summary: The utilization of negative pressure for medicinal purposes dates back to 600 bc. The U.S. military has been engaged in continuous overseas combat operations since 2001. Negative-pressure wound therapy has been in use in the treatment of casualties from these operations since 2004. It represents a new standard of practice in combat wound care; it promotes granulation tissue formation and creates mechanical forces supporting wound contraction, facilitating definitive wound closure. This article describes (1) the use of negative-pressure wound therapy in combat casualty care, (2) inherent challenges of its use in theater of operations and across the echelons of care, (3) modifications of this wound therapy to meet military-specific needs, and (4) future directions with this novel wound care modality. (*Plast. Reconstr. Surg.* 127 (Suppl.): 117S, 2011.)

HISTORY OF NEGATIVE-PRESSURE WOUND CARE IN MEDICINE

The utilization of negative pressure for medicinal purposes dates back to 600 BC, when it was used to treat human envenomation. By the third quarter of the twentieth century, negative pressure was being used with increasing frequency for the treatment of open wounds. During the 1970s and 1980s, a Russian negative-pressure system connected to drainage canisters was used to treat various acute suppurative conditions of soft tissue.¹⁻³ In 1986, Bagautdinov developed a vacuum aspiration system that utilized polyurethane foam and incorporated a mini-irrigator tube to allow for simultaneous cleansing and suction of

the wound.⁴ This was similar in principle to Svedman's intermittent or continuous irrigation/suction system incorporating a felt dressing applied to an open wound surface, described earlier.^{5,6} Chariker and colleagues described a closed irrigation/suction system for treating ventral abdominal wounds complicated by enterocutaneous fistula, using gauze dressings that conformed to the wound bed.⁷ In 1997, Argenta and Morykwas reported experimental findings of negative-pressure-related increases in rate of wound granulation tissue formation, reduction in local tissue bacterial counts, and increased random-pattern flap survival; they also reported their clinical experience with vacuum-assisted closure using the same open-cell foam (polyurethane sponge) and continuous negative pressure (125 mmHg below ambient pressure) on 300 acute and chronic open wounds, finding improved wound bed preparation (enhanced granulation tissue formation).⁸

Commercial development initiated in the early 1990s resulted in the widespread use and adoption of negative-pressure wound therapy. Over the next decade, negative-pressure wound therapy was rapidly incorporated into standards of wound care practice, being regarded as a practical and cost-effective treatment modality. The Kinetic Concepts, Inc. (San Antonio, Texas) Vacuum-Assisted Closure Therapy System was the original

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Received for publication May 24, 2010; accepted September 7, 2010.

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DOI: 10.1097/PRS.0b013e3181fd344e

Disclosure: Neither of the authors has a financial interest in any of the products, devices, or drugs mentioned in this article.

Report Documentation Page			Form Approved OMB No. 0704-0188	
<p>Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p>				
1. REPORT DATE 07 SEP 2010	2. REPORT TYPE	3. DATES COVERED 00-00-2010 to 00-00-2010		
4. TITLE AND SUBTITLE Negative-Pressure Wound Therapy in the Military: Lessons Learned			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Complex Wound and Limb Salvage Center and ,the Combat Wound Initiative Program,Walter Reed Army Medical Center,Washington,DC			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited				
13. SUPPLEMENTARY NOTES Negative-pressure wound therapy in the military: lessons learned. Plast ic and Reconstructive Surgery 2011 Jan;127 Suppl 1:117S-130S Complex Wound and Limb Salvage Center and the Combat Wound Initiative Program, Walter Reed Army Medical Center, Washington, D.C., USA				
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15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF: a. REPORT b. ABSTRACT c. THIS PAGE unclassified unclassified unclassified			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 14
			19a. NAME OF RESPONSIBLE PERSON	

commercially available negative-pressure wound therapy product in the United States. The system consists of reticulated open-celled polyurethane foam manifold material (GranuFoam Dressing; Kinetic Concepts), a pressure-sensing control mechanism (Therapeutic Regulated Accurate Care Technology; Kinetic Concepts), and therapy units with computerized feedback algorithms (Vacuum-Assisted Closure Therapy System; Kinetic Concepts). An alternative negative-pressure wound therapy technology emerged in 2003 that utilized nonfoam constituents and was based on the technique utilized by wound care specialists in Russia^{3,5,9} and described by Chariker and Jeter (Blue Sky, then Smith and Nephew, London, United Kingdom).^{10–14} As with the Kinetic Concepts system, the Smith and Nephew Renasys EZ system is indicated for a variety of acute, traumatic, and chronic wounds and interfaces with the RENASYS-G dressing kit, which utilizes a gauze interface and is considered useful for circumferential, tunneling wounds and selected fistulas.

Negative-pressure wound therapy has gained popularity since the time the war in Iraq began, due to its versatility and broad range of indications. In 2009, the sales of negative-pressure wound therapy-related products exceeded \$1 billion U.S., encompassing over half the market for wound closure technologies.¹⁵ Kinetic Concepts was the leader of this largest-ever market in wound care during the first 5 years of its rapid development. After acquisition of Blue Sky Medical, Smith

and Nephew PLC entered the market space in 2007 with its array of negative-pressure wound therapy products. Over the past few years, other companies (ConvaTec, Inc.; Innovative Therapies, Inc.; Medela, Inc.; and NovaSpine LLC) have entered the same market, which is becoming increasingly competitive.

Operation Iraqi Freedom and Operation Enduring Freedom began after the September 11, 2001, terror attack on the United States. Operation Iraqi Freedom started on March 20, 2003, in Iraq, and Operation Enduring Freedom started in Afghanistan in October of 2001. As of April 20, 2010, there have been casualties in the thousands of both killed in action ($n = 5,430$) and wounded in action, not returned to duty ($n = 17,111$) (Table 1; available at <http://www.defense.gov/NEWS/casualty.pdf>; accessed April 20, 2010).¹⁶

There has been a paradigm shift in the treatment of war wounds during the current conflicts. Reliance on traditional wound management principles for the treatment of war wounds is limiting, because the nature of war wounds makes them unsuitable for conventional periodic, saline-soaked gauze wound dressing changes. The combined effects of blast and penetrating fragments from improvised explosive devices, in an era of advanced protective body armor, account for the high incidence of now survivable multiple penetrating complex and extensive wounds to the extremities (Figs. 1 through 3). A retrospective analysis of U.S. service members receiving treatment for war

Table 1. Operation Iraqi Freedom and Operation Enduring Freedom U.S. Casualty Status Fatalities as of April 20, 2010, 10:00 a.m. EDT*

	Total Deaths	KIA	Nonhostile	WIA RTD†	WIA Not RTD†
OIF U.S. military casualties by phase					
Combat operations—March 19, 2003, through April 30, 2003	139	109	30	116	429
Postcombat operations—May 1, 2003, through present	4242	3364	878	17,725	13,508
OIF U.S. Department of Defense civilian casualties	13	9	4		
Totals	4394	3482	912	17,841	13,937
OEF U.S. military casualties					
In and around Afghanistan‡	956	747	209	2455	3173
Other locations§	78	8	70	1	
OEF U.S. Department of Defense civilian casualties	2	1	1		
Worldwide total	1036	756	280	2455	3174

OIF, Operation Iraqi Freedom; OEF, Operation Enduring Freedom; KIA, killed in action; WIA, wounded in action; RTD, returned to duty.

*Operation Iraqi Freedom includes casualties that occurred on or after March 19, 2003, in the Arabian Sea, Bahrain, Gulf of Aden, Gulf of Oman, Iraq, Kuwait, Oman, Persian Gulf, Qatar, Red Sea, Saudi Arabia, and United Arab Emirates. Prior to March 19, 2003, casualties in these countries were considered Operation Enduring Freedom.

†These columns indicate the number of service members who were wounded in action and returned to duty within 72 hours and wounded in action and not returned to duty within 72 hours. To determine the total wounded-in-action figure, add the columns "WIA RTD" and "WIA Not RTD" together. These figures are updated on Tuesday unless there is a preceding holiday.

‡Operation Enduring Freedom (in and around Afghanistan) includes casualties that occurred in Afghanistan, Pakistan, and Uzbekistan.

§Operation Enduring Freedom (other locations) includes casualties that occurred in Guantanamo Bay (Cuba), Djibouti, Eritrea, Ethiopia, Jordan, Kenya, Kyrgyzstan, Philippines, Seychelles, Sudan, Tajikistan, Turkey, and Yemen.



Fig. 1. Wounds of war. (Left) Open radial forearm fracture. (Right) Open distal femur fracture with external fixation.

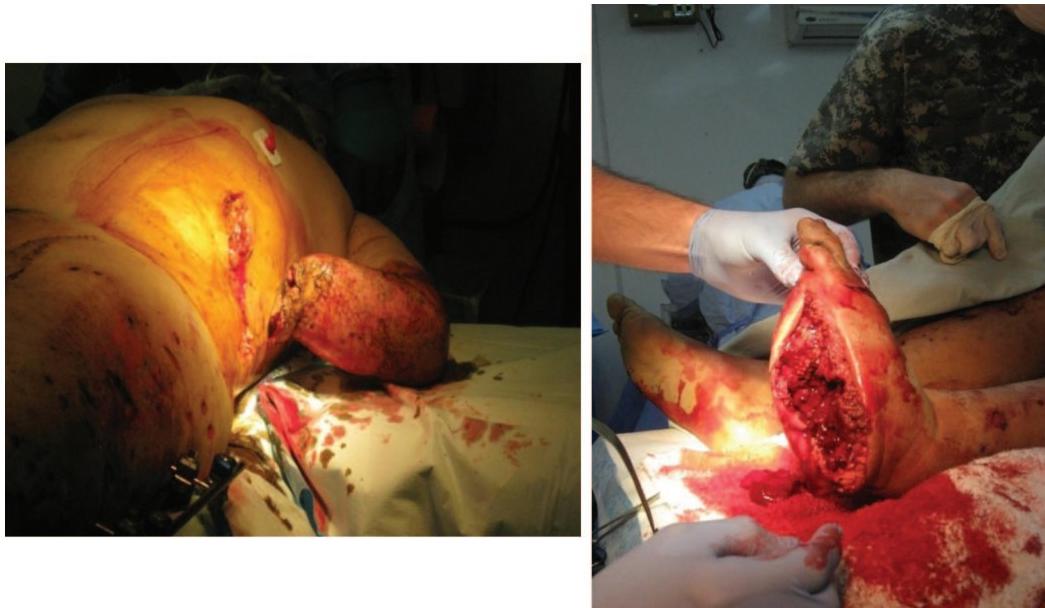


Fig. 2. Wounds of war. (Left) Traumatic forearm amputation, penetrating truncal injury, and open distal femur fracture with external fixation. (Right) Complex soft-tissue and osseous disruption of the foot by a land mine.

wounds showed that 78 percent of injuries were caused by an explosive mechanism, the highest percentage seen in a large-scale conflict.¹⁷ A treatment paradigm aimed at early, definitive closure of these initially contaminated, complex wounds has been developed and in use over the past decade of armed conflict. The benefits of negative-pressure wound therapy became rapidly apparent, and Geiger et al. reported negative-pressure wound therapy/reticulated open-celled polyurethane foam use in 46 percent of Operation Enduring Freedom patients in March of 2003, which expanded to over 90 percent of admitted wounds in September of 2003.¹⁸

Combat casualties typically undergo multiple operations (mean, four \pm two) in the field across the levels of care, which are initially intended to achieve damage control or surgical stabilization through hemorrhage control and preservation of limb perfusion, wound débridement/irrigation/packing and/or vacuum-assisted closure, fasciotomy, amputation, external fixation, and fracture stabilization (Figs. 1 through 3). While hospitalized in level V medical centers (e.g., Walter Reed Army Medical Center, Washington, D.C.) within the continental United States, combat casualties require multiple operations (mean, two \pm one operations per patient; range, one to nine) that are intended

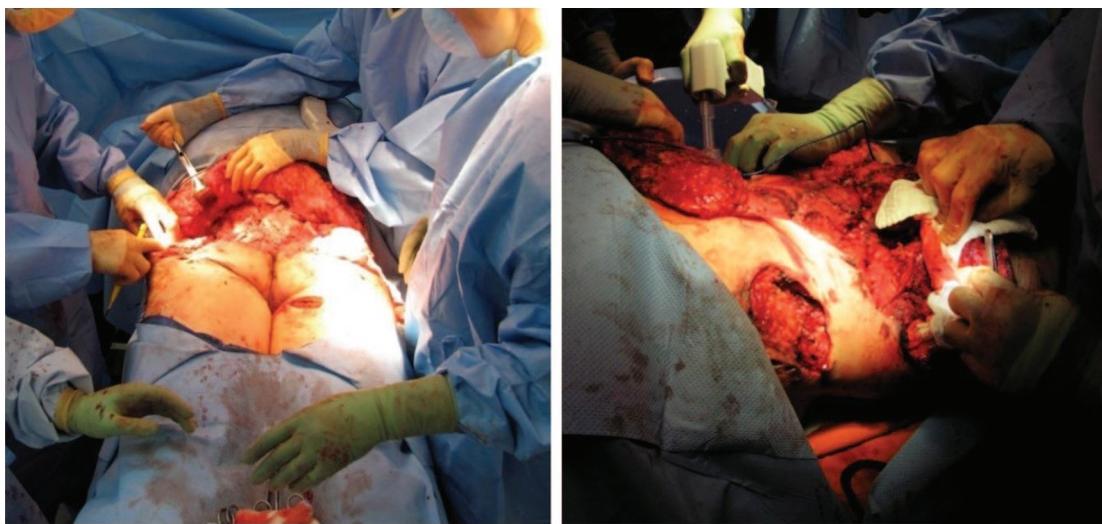


Fig. 3. Wounds of war. Improvised explosive device causing massive disruption of the gluteal region, anal sphincter, and lumbosacral spine.

to be definitive in nature and follow multiple soft-tissue wound débridement/irrigation/vacuum-assisted closure treatments, aimed at wound bed preparation with control of bioburden to facilitate rapid, definitive closure or coverage.¹⁸ Negative-pressure wound therapy has been a key component of rapid wound bed preparation in the care of wartime casualties from level II through level V care since 2004. It has been relied on for exudate clearance, promotion of granulation tissue, and mechanical wound contraction; it represents a new standard of practice. Anecdotally, it has been the authors' experience that patients arrive in the United States with multiple negative-pressure wound therapy applications to their various wounds. It is not uncommon to have several pressure machines used on a single patient during transport.

MILITARY HEALTH SYSTEM LEVELS OF CARE

The Military Health System is an integrated system of medical and surgical service support extending from the point of wounding (level I: self-aid/buddy aid/medic/combat life saver)—via critical care air transport—to level V military medical centers (e.g., Walter Reed Army Medical Center) within the continental United States providing the full spectrum of definitive care and rehabilitation. There are five levels (I, II, III, IV, and V) of care, with each subsequent level (II+) having the capability of its lower level and expanding on that level of combat casualty care. Level I through IV treatment facilities are shown in Figure 4.

Level I combat casualty care is rendered near the point of wounding through self-aid/buddy aid/

medic/combat life saver and the battalion aid station. Level I providers are trained to identify and treat immediate life-threatening, potentially reversible conditions (immediate treatment), including airway obstruction (cricothyroidotomy), tension pneumothorax (percutaneous catheter decompression), and exsanguinating hemorrhage (topical hemostasis and early tourniquet application).

Level II includes mobile forward surgical teams providing resuscitative or damage control surgery, a 20-person team with three general surgeons, one orthopedic surgeon, and two certified nurse anesthetists capable of providing continuous operations (up to 30 surgical procedures) on two operating tables over a 72-hour period. The forward surgical team has limited radiographic, laboratory, blood bank (20 units packed red blood cells, types O positive and O negative), intensive care (up to eight patients), and patient-holding (up to 72 hours) capability. The primary intent of the forward surgical team is rapid surgical stabilization (e.g., tube thoracostomy, damage control laparotomy, external fracture fixation, fasciotomy, and stenting or repair of major vasculature) and tactical evacuation to the next level of care (Fig. 4).

The Army's modular combat support hospital (*level III* care), consisting of 44- to 248-bed capability [intensive care unit (up to $n = 60$), intermediate care ward (up to $n = 140$), and neuro-psychiatric (up to $n = 20$) and minimal care ward (up to $n = 40$)], is the highest level of casualty care within the combat zone, which includes damage control resuscitation, transfusion (type-specific

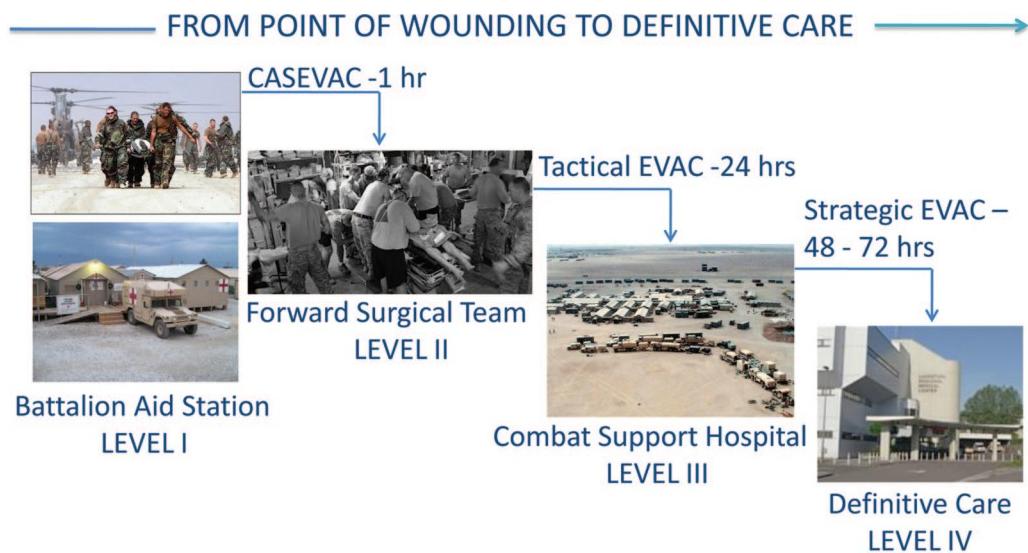


Fig. 4. Military Health System levels of care, from point of wounding first responder/battalion aid station to definitive surgical level IV care, Landstuhl Regional Medical Center.

packed red blood cells, fresh frozen plasma, cryoprecipitate), cross-sectional imaging (computer tomography) and interventional radiology, damage control, definitive and reconstructive surgery (general, orthopedic, trauma, thoracic, burn, urologic, neurosurgical, dental, and oral-maxillofacial, with certified registered nurse anesthetists and anesthesiologists), perioperative and critical care, physical therapy, and patient-holding capability. The full complement of the combat support hospital has six operating tables and resources to support 96 operating hours/day. Strategic evacuation (Figs. 1 through 3) within 24 to 72 hours is supported by the aeromedical evacuation system to include critical care air transport teams to the next level outside the combat zone. This evacuation system is capable of moving 1000 or more casualties per month and has provided continued resuscitation and advanced (critical) casualty care for both Operation Iraqi Freedom (Fig. 5, *above* and *below*) and Operation Enduring Freedom (Fig. 5, *above*) and has adjusted effectively to the shifts in casualty volume over the past decade (Fig. 5).

Level IV care is situated outside of combat zone but within the communication zone of the wartime theater of operations, which provides reassessment and diagnostic evaluation and definitive, specialized medical-surgical care for casualties en route to the United States, as well as more intensive rehabilitative and convalescent care for patients expected to return to duty in Iraq and Afghanistan. Landstuhl Regional Medical Center

(Fig. 4) is the common pathway node through which all Operation Enduring Freedom/Operation Iraqi Freedom casualties pass through for additional care (mean hospital stay, 2 to 4 days), en route to tertiary, university-affiliated medical centers (e.g., Brooke Army Medical Center and Walter Reed Army Medical Center) within the United States (*level V*). These medical centers of excellence provide multidisciplinary care to attain maximum functional restoration and quality-adjusted living. Landstuhl Regional Medical Center is also the first step in the multidisciplinary rehabilitative care for service members with catastrophic wounds of war.

Even though the nature of combat casualty care in the initial level I/II/III may seem rudimentary (resuscitative and damage control interventions of necessity), on-going refinement of medical-surgical care of the war wounded has been a key facet of modern-day military medicine. This critical component has been enabled by rapid communications, global electronic medical records, rapid evacuation (particularly critical care air transport teams), weekly teleconferences among in-theater combat support hospitals, level IV (Landstuhl Regional Medical Center, Germany) and level V facilities (Brooke and Walter Reed Army Medical Centers), and a theater-wide electronic trauma-tracking database, utilizing a trauma systems-based approach.

The Military Health System has implemented a modern combat trauma system, the Joint Theater Trauma System and the Joint Theater Trauma

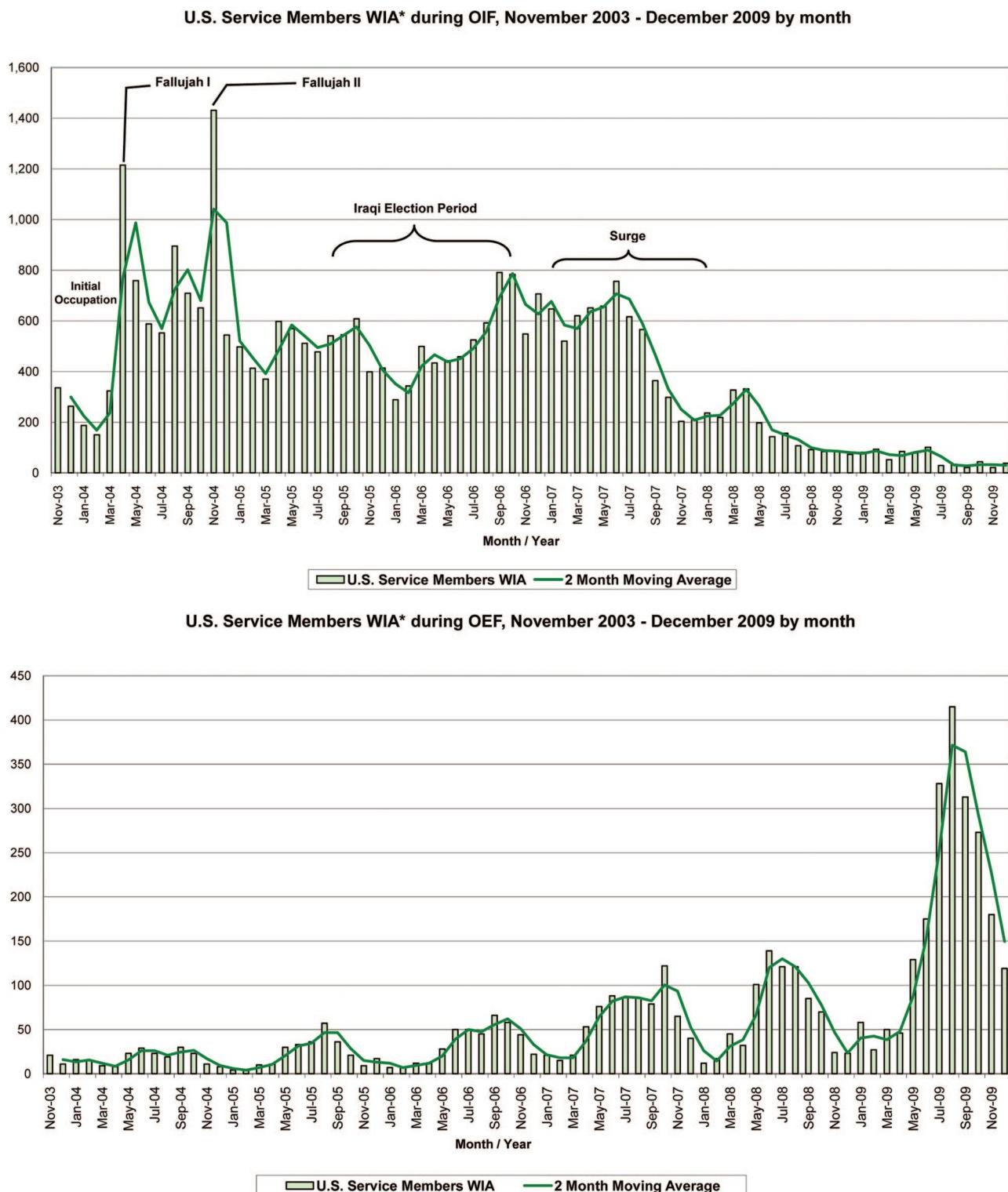


Fig. 5. U.S. service members wounded in action during (above) Operation Iraqi Freedom (OIF) and (below) Operation Enduring Freedom (OEF), November of 2003 to December of 2009, by month. The operational definition used for wounded-in-action data includes all patients classified as died of wounds, those admitted to a medical treatment facility and survived/evacuated, and those who returned to duty within 72 hours of injury. Green bars, U.S. service members; green line, rolling monthly average. WIA, wounded in action.

Registry, based on existing civilian trauma systems evident in the American College of Surgeons Committee on Trauma and National Trauma Data Bank, aimed at improving survival after battlefield injury. The Joint Theater Trauma System has established performance improvement metrics and developed evidence-based clinical practice guidelines that provide clinical decision support far forward on the battlefield and across the spectrum of combat trauma system care. The apparent success of the military's Joint Theater Trauma System is evident in a posthospital admission mortality rate in battlefield injured, which is nearly equivalent to age-matched civilian cohorts (5.2 versus 4.3 percent).¹⁶

The exigencies of wartime medicine pose unique practical and ethical challenges of designing and conducting randomized controlled trials; however, a battlefield outcomes database has enabled case-controlled and cross-sectional studies to compare trauma outcomes across the levels of care within the Military Health System and with established civilian norms. The United States Army Institute of Surgical Research is the center of operations for the Joint Theater Trauma Registry, which was created to record and archive comprehensive combat casualty epidemiology, treatment, and outcomes data.

The Joint Theater Trauma System/Joint Theater Trauma Registry serves as the fundamental basis for the 27 established clinical practice guidelines,^{19–23} which were developed and implemented by subject matter experts in response to unmet needs identified in theaters of war and across the spectrum of battlefield trauma care. These clinical practice guidelines serve as the backbone of the system-wide Joint Theater Trauma System Performance Improvement Initiative. Application of the clinical practice guidelines is monitored, and the guidelines are reviewed and developed further in the context of outcome data obtained from the Joint Theater Trauma Registry; they are updated in nearly real-time to provide teams with accurate, evidence-based guidelines on which to improve combat casualty care across the spectrum of medical and surgical capability.

CLINICAL PRACTICE GUIDELINE: SOFT-TISSUE INJURIES, BATTLE- RELATED WOUND DÉBRIDEMENT, WASHOUT, AND IRRIGATION

Specific Aim

The specific aim of the clinical practice guideline is to minimize morbidity, prevent infection, preserve function, and save limbs and lives through early, aggressive wound care (Fig. 6).



Fig. 6. (Above) Through-knee amputation. (Center) Adequately débrided traumatic lower extremity amputation and preserved viable posterior skin/soft-tissue flap. (Below) Residual limb open wound negative-pressure wound therapy (vacuum-assisted closure negative-pressure wound therapy).

Background

The most common surgical procedure performed in the combat theater is wound débridement and irrigation. The devastating force of the

modern-day improvised explosive device and the uniformly contaminated nature of war wounds make timely surgical débridement and removal of devitalized tissue, debris, blood, bacteria, and foreign bodies imperative so as to prevent local wound complications and reduce the systemic effects associated with such wounds.

Antibiotics are not a replacement for this time-tested surgical approach. The priorities of surgical management of war wounds are as follows: life-saving intervention; limb-sparing treatment (fasciotomy, vascular shunting or repair); early (within 6 hours of injury) wound débridement and irrigation; therapeutic antibiotics; sterile dressings with or without negative-pressure wound therapy; and fracture immobilization. The extent of initial débridement relies on the judgment of the surgeon. While the intent is to remove all devitalized soft tissue in the wound, potentially and clearly viable tissue should be preserved for definitive reconstruction at higher levels of care, and potentially viable tissue should be reassessed through serial wound explorations. While high-pressure pulsatile lavage devices may be effective in the civilian trauma setting, they are not recommended for use in the combat theater, as they may cause tissue damage and worsen bioburden in war wounds, when compared with bulb syringe irrigation.²⁴

Evaluation and Treatment

Wounds sustained on the battlefield should undergo débridement and irrigation as soon as feasible (preferably within 6 hours) after stabilization and control of life-threatening injuries. The frequency of repeated wound débridement and irrigation depends on the nature, severity, and contamination of the wound and should be conducted at least every 48 hours. Significantly contaminated wounds require more frequent washouts, which should be timed immediately before aeromedical evacuation to avoid prolonged delays between treatments.

Wound irrigation is performed until the wound is clean after surgical removal of debris and nonviable tissue. Simple bulb irrigation or gravity irrigation is the preferred method for irrigation. Large-bore gravity-run tubing is the recommended quick and practical method of irrigation (Fig. 7). The irrigation fluid may be sterile isotonic saline (preferred), sterile water, or potable tap water, as all have similar usefulness, efficacy, and safety.^{25–29}

Bacterial loads drop logarithmically with increasing volumes of irrigation. Sufficient irrigation volumes should be utilized to remove all



Fig. 7. Large-bore, gravity-run, Y-type urologic cystoscopy tubing for open wound irrigation.

grossly apparent debris. Irrigation volume recommendations are based on wound volume as estimated by the surgeon: 1 to 3 liters, 4 to 8 liters, and 9 or more liters for small, moderate, and large wounds or wounds with evidence of heavy contamination, respectively. Combat wounds should be left open initially and allowed to heal by secondary intention or undergo delayed (3 to 5 days postwounding) primary closure or coverage (split-thickness skin grafts, myocutaneous flaps, and so on) after serial evaluations, once the wound appears clean, well-perfused, and free of critical contamination (Fig. 8). Closure or coverage of the wound should occur at a definitive level (IV/V) facility. Antibiotics to cover common Gram-positive organisms are administered intravenously before wound exploration along with tetanus prophylaxis.

Military surgeons must employ multiple reconstructive techniques to achieve closure and preserve/recreate function. Often, the combat casualty has large areas that need soft-tissue wound closure in addition to closure of amputations or fasciotomy sites. Helgeson et al. described use of a dermal replacement substitute (Integra Bilayer Wound Matrix; Integra Life Sciences Corporation, Plainsboro, N.J.) in conjunction with negative-pressure wound therapy to close major soft-tissue defects not suitable for split-thickness skin grafts, particularly wounds with exposed bone and/or tendon.³⁰ The authors describe a very successful approach to obtaining coverage (typically within 3 weeks) of these complex wounds after adequate wound bed preparation with serial débridement/irrigation/vacuum-assisted closure involving bioartificial dermal substitute grafting onto the wound bed in combination with bedside or clinic vacuum-assisted closure dressing changes every 3 to 4 days,



Fig. 8. (Above, left) Adequate wound bed preparation of a host-nation military service member with an improvised explosive device blast/penetrating injury to the right lower leg, creating an open Gustillo type IIIC tibia/fibula fracture. (Above, right) External fixation and four-compartment fasciotomy–lateral fasciotomy incision. (Center, left) Right medial leg wound with medial fasciotomy incision and proximal split-thickness skin graft donor site. (Center, right) Lateral radiograph of delayed intramedullary tibial fixation and (below, left) skin grafting of lateral fasciotomy incision. (Below, right) Negative-pressure wound therapy to medial right lower leg wound.

followed by definitive, delayed split-thickness skin grafts.³⁰ This is an approach that may reduce the need for more complex flap coverage (Figs. 9 and 10). In addition, the authors showed that it is pos-

sible to take a thinner skin graft to achieve final closure due to the neodermis that was formed. Leininger et al. found that the length of stay was substantially reduced with negative-pressure wound

therapy/reticulated open-celled polyurethane foam, compared with closure via secondary intention or delayed grafting, and reported a mean time to closure of 4 days in 77 Iraqi patients with 88 soft-tissue wounds.³¹



Fig. 9. Bioartificial dermal substitute combined with vacuum-assisted closure for management of combat-related soft-tissue wounds. Combat wound after improvised explosive device. Reprinted from Helgeson MD, Potter BK, Rvans KN, Shawen SB. Bioartificial dermal substitute: A preliminary report on its use for the management of complex combat-related soft tissue wounds. *J Orthop Trauma* 2007;21:394–399.

INHERENT CHALLENGES WITH NEGATIVE-PRESSURE WOUND THERAPY IN THEATER OF OPERATIONS AND ACROSS THE EVACUATION CHAIN

The Kinetic Concepts, Inc., vacuum-assisted closure system has been used, almost exclusively, in far-forward surgical treatment facilities and during ground and air medical evacuation, as well as in military medical centers within Germany and the United States. Clinical applications have been diverse, most notably to treat soft-tissue blast/missile injuries and thermal injury and to provide temporary abdominal closure.³¹ There have been a number of vacuum-assisted closure system limitations identified during the initial period of use (2004 to 2005), particularly during patient transport. The long transport times from the battlefield to the United States pointed to key device-related constraints—portability and ability to function for extended periods with limited power supply. The system requires an external power source in the event of battery failure, and battery life with the original system was limited. The loss of system suction during periods of battery power failure and overlying adhesive failure provided further opportunities for system improvement. The vacuum-assisted closure system profile was initially not conducive to patient mobility with ease in this environment. The



Fig. 10. Bioartificial dermal substitute combined with vacuum-assisted closure for management of combat-related soft-tissue wounds. Multiple incisions and drainage, flexor hallucis longus transfer, Integra/vacuum-assisted closure, and split-thickness skin graft. Reprinted from Helgeson MD, Potter BK, Rvans KN, Shawen SB. Bioartificial dermal substitute: A preliminary report on its use for the management of complex combat-related soft tissue wounds. *J Orthop Trauma* 2007;21:394–399.

earliest vacuum-assisted closure system reticulated open-celled polyurethane foam lacked antimicrobial properties desired for the management of contaminated wounds between frequent, repeated wound débridements.

MODIFICATIONS OF NEGATIVE-PRESSURE WOUND THERAPY TO MEET THE SPECIFIC NEEDS OF COMBAT CASUALTY CARE

Early, practical solutions to unmet needs for negative-pressure wound therapy were implemented: utilization of standard Impact (Impact Instrumentation, Inc., West Caldwell, N.J.) suction devices during periods of battery failure or lack of external power, introduction of silver impregnated reticulated open-celled polyurethane foam (Silver GranuFoam Dressing), and finding that the reticulated open-celled polyurethane foam/adhesive could be left intact without suction for periods of time during casualty care. When required and if possible, the vacuum-assisted closure system tubing is clamped to sustain negative pressure for as long as needed during evacuation. Appropriate negative-pressure wound therapy is then reinstated immediately upon availability of power or arrival at the destination facility. However, leaving a vacuum-assisted closure dressing on a wound requiring further débridement of devitalized tissue predictably results in a putrid smelling wound, best avoided through earlier vacuum-assisted closure dressing exchange.

It is generally accepted that leaving reticulated open-celled polyurethane foam/adhesive on a wound without suction poses risks of wound infection; however, it is the authors' experience that this technique can be applied under austere circumstances and logistical challenges safely under

appropriate monitoring. Absent that, non-negative-pressure wound therapy modalities, such as saline-soaked gauze dressings, are appropriate in these situations.

The Vacuum-Assisted Closure Freedom Therapy Unit was introduced in 2004 to 2005 and addressed the need for a lightweight system with acceptable battery life, designed for portability (Fig. 11). This unit weighs less than 5 pounds, has up to 12 hours of battery life, and has an "in-line" power module with a nondetachable alternating current cord to reduce risk of inadvertent disconnection of power cord. Initially, use was limited to individuals undergoing treatment in theater of operations, due to concerns of the product's ability to function appropriately at reduced ambient pressure in evacuation aircraft. The demonstrated ability to reduce infectious complications, facilitate timely delayed primary closure, and decrease hospital length of stay relative to established military doctrine for the treatment of war wounds³⁰ has contributed to ongoing efforts to critically assess the suitability of this product for use in air transport vehicles. Vacuum-Assisted Closure Freedom Therapy was tested according to the Joint Airworthiness Certification Test Protocol and validated for appropriate functionality at cabin pressures typical of critical care air transport teams/MEDEVAC flights. Vacuum-assisted closure system modifications allowed casualties to receive continuous negative-pressure wound therapy as they progressed from far-forward surgical treatment facilities to tertiary care facilities in Germany (level IV) and the United States (level V).

An important consideration for use of negative-pressure wound therapy devices in the forward deployed setting is the availability of dressings with antimicrobial capabilities. The ability to



Fig. 11. Vacuum-Assisted Closure Freedom Therapy unit, a lightweight (<5 pounds) system with up to 12 hours of battery life, designed for portability. It has an "in-line" power module with nondetachable alternating current cord to reduce risk of inadvertent power cord. Image provided courtesy of Kinetic Concepts, Inc.

provide effective negative-pressure wound therapy and effective protection to the wound in the presence of polymicrobial contamination or infection has improved. This was enabled following the introduction and increasingly frequent use of adjunct dressings, such as the vacuum-assisted closure GranuFoam Silver Dressing.

FUTURE DIRECTIONS

The ABThera Open Abdomen Negative-Pressure Therapy System (Kinetic Concepts.) was designed to provide temporary bridging of open abdominal wounds with exposed viscera, for which primary closure is not possible and/or repeated entry of the peritoneal cavity is necessary. The system is appropriate for use when temporary abdominal closure is desired following soft-tissue blast/missile injuries, massive blunt trauma, penetrating trauma, extensive thermal injuries, treatment of abdominal compartment syndrome, or damage-control surgery.

The system provides medial traction on the abdominal wall, reducing loss of domain. As the application of the system does not require the use of sutures, fascial damage is minimized. Other possible benefits include isolating the viscera and abdominal contents from the external environment and reducing risk of entero-atmospheric fistula while allowing rapid access for reentry.

A porcine open abdomen model was developed to assess the systemic inflammatory response associated with intraabdominal sepsis and hemorrhage. Kubiak et al.³² established this model of intraabdominal visceral ischemia/reperfusion injury followed by contamination of bowel contents. Passive drainage or negative-pressure therapy (similar to the ABThera system) is applied to the open abdomen 12 hours after injury. The negative-pressure system removed significantly more fluid from the abdomen, had lower levels of systemic inflammatory markers, such as tumor necrosis factor-alpha and interleukin 6, and had significantly improved intestine, lung, kidney, and liver histopathology relative to the passive drainage controls.³³ These findings engendered the hypothesis that open abdominal negative-pressure wound therapy modulates systemic inflammatory response and reduces sepsis-induced multiorgan dysfunction associated intraabdominal hypertension. Other studies have suggested that negative-pressure wound therapy has the potential to decrease the systemic effects of massive muscle trauma resulting from prolonged crush/ischemic injury.³⁴

ABThera was developed to address unmet needs in the treatment of the open abdomen and

to serve as the basis for further testing of the effects of negative-pressure wound therapy on the systemic inflammatory response in large open wounds. Similarly, the Prevena Incisional Management System (Kinetic Concepts) was developed based on the hypothesis that early application of negative pressure may reduce ongoing local inflammatory responses potentially disruptive of normal healing processes as well as decrease swelling and the incidence of hematoma and seroma formation in patients at risk for wound complications. Several authors have reported successful outcomes using negative-pressure wound therapy over a variety of clean closed surgical incisions, including those following coronary artery bypass grafting,^{35,36} transmetatarsal amputation and abdominal hysterectomy,³⁶ and high-risk fractures after high energy trauma.³⁷ The Prevena Incision Management System is intended to manage the environment of closed surgical incisions and surrounding intact skin in patients at risk for developing postoperative complications, such as operative-site infection, by maintaining a closed environment via the application of negative pressure to the incision. A Prevena Incision Dressing skin interface layer containing silver was developed with the aim of reducing microbial colonization in the dressing. Although the use of negative-pressure wound therapy over incisions by the previously cited authors has initially been positive, randomized clinical trials are required to definitely assess the capability of this system to decrease edema and the incidence of complications, such as seromas, hematomas, and wound infections.

CONCLUSIONS

Negative-pressure wound therapy has proven to be both an efficacious and a necessary treatment modality for complex war wounds. The severity of the various wounds, need for frequent débridement in preparation for definitive closure or coverage, and rapid transfers among multiple levels of care create a unique and multifaceted treatment paradigm for military health care providers. The use of clinical practice guidelines greatly assists in standardizing therapy regimens among all levels of care. Obstacles to negative-pressure wound therapy, including airworthiness, have been addressed and allow for continuity of care and further research to be undertaken in this complex patient population. Negative-pressure wound therapy is evolving with new applications designed for specific conditions (open abdomen, at-risk surgical incisions) that have the potential to improve outcomes.

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ACKNOWLEDGMENTS

This clinical research effort was supported, in part, by the Combat Wound Initiative Program, Washington, D.C.

The authors acknowledge Tiffany Felix for her invaluable assistance supported in part by the Henry M. Jackson Foundation for the Advancement of Military Medicine. They are grateful to the members and staff of the Combat Wound Initiative Program for their consistent support of this collaborative research effort. Most importantly, the authors acknowledge the significant contributions of healthcare providers at the Complex Wound and Limb Salvage Center, Washington, D.C., without whom the committed, compassionate, and highly capable, multidisciplinary care of our patients with wounds would not have been possible. The authors are dedicated to the care of the war wounded and serve them in the spirit of Hippocrates: "Cure sometimes, treat often, comfort always."

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